



Invisibility Cloak: extremetech.com

A Magnetic Field Cloaking Device

Enabling a dipole spectrometer in the high rapidity detector at the EIC without hurting the primary accelerator beams

K. Boyle¹, **R. Cervantes**², **B. Coe**², K. Dehmelt², A. Deshpande^{2,1*},
N. Feege^{2*}, Y. Goto³, R. Gupta⁴, T. K. Hemmick², **P. Karpov**², R. Lefferts²,
A. Lipski², I. Nakagawa³, B. Parker⁴, J. Seele¹, V. Ptitsyn⁴

¹RBRC, ²Stony Brook University, ³RIKEN, ⁴Brookhaven National Laboratory, * Contact people
Bold Type: Students

Rational:

We know from studies so far, that in the large rapidity regions of EIC we will need special spectrometer magnet design to momentum analyze the particles.

- π , K, p in the range of high-10s of GeV
- scattered e's with 5-30 GeV depending on the initial beam energy

A dipole magnet would be simple and ideal: A 1.0T magnet over $\sim 1\text{m}$ length and three position resolution plans each with $\sim 60\mu\text{m}$ precision would result in $\delta p/p \sim 0.2\%(p)$ (without considering multiple scattering).

However, a **1Tm dipole would also result in:**

- For 10 GeV electrons:
 - Significant synchrotron radiation
 - a shift of $\sim 30\text{ mrad} \rightarrow \sim 15\text{ cm}$ at the triplet at 5m
 - a spin rotation of $0.573\text{ rad} = 32.8\text{ degrees}$
- For 100 GeV protons:
 - a shift of $3\text{ mrad} \rightarrow \sim 1.5\text{ cm}$ the 5m triplet
 - A spin rotation of $0.681\text{ rad} = 39.0\text{ degrees}$

These are not desirable consequences!

Like to avoid, while still keeping the option of using the dipole.

Shielding the accelerator beams

Not a unique or first-time issue addressed for the experimenters::

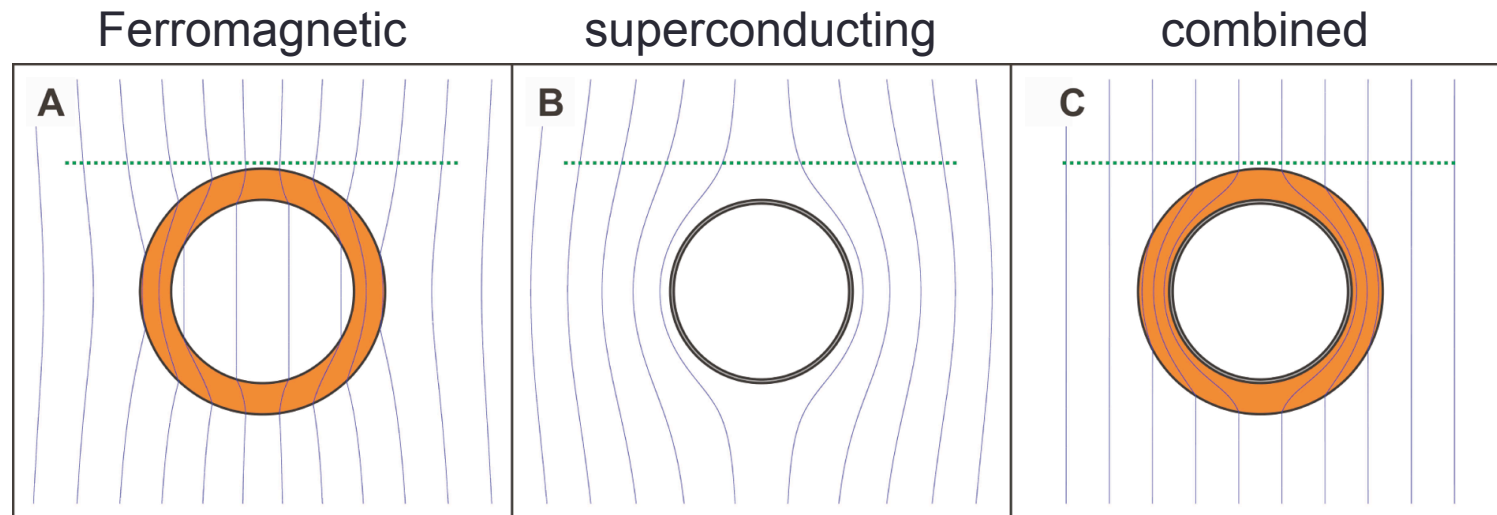
In the past two approaches have been tried:

- a) **Compensator magnet:** puts additional constraints on the accelerator/IR Design in a limited space
- b) **Superconducting tubes** around beam pipe: distort the field outside the volume

A new and clever idea has been experimentally demonstrated with fairly low priced and easily available material: (for medical application, small size, low fields)

- F. Gomory et al., Experimental Realization of a Megnetic Cloak, Science Vol. 335, No. 6075, pp. 1466-1468, March 2012

The cylindrical magnetic cloak



Magnetic permeability of ferromagnetic layer $\mu = \frac{R_1^2 + R_2^2}{R_2^2 - R_1^2}$

$R_{1/2}$ are the inner and outer radii of the ferromagnetic layer.
Thickness of the Super conducting layer does not matter.

See detailed of the calculation: F. Gomory et al, Science 335, 1466 (2012)
DOI: 10.1126/science.1218316

Construction of the Bilayer:

Inner Super Conducting Layer

- 1micron layer of ReBCO deposited on 100micron metallic substrate, able to carry 400A current in 12mm wide tape at 77K
- *Changing the number of turns wrapping allows to vary the strength of B field expulsion.*

Outer Ferromagnetic Layer

- Wound from 100 micron thick $\text{Fe}_{18}\text{Cr}_9\text{Ni}$ alloy sheet
- *Changing the number of turns allows to adjust the magnetic response of the outer shell.*

Cylindrical mandrel of textile enforced plastic: was wrapped with 2 layers of 12mm wide SC tape . 70 micron kapton layer was inserted between them (avoids short circuit)

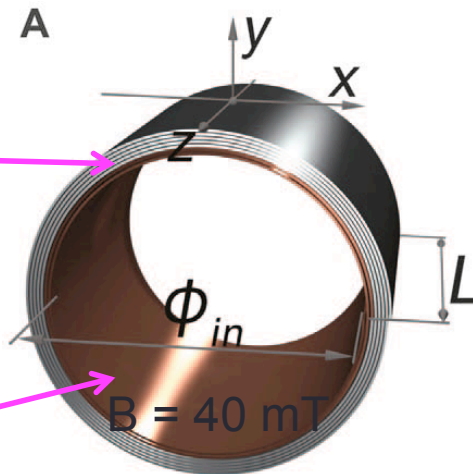
12mm wide strips of FeNiCr alloy were cut long enough to make 7 turns alternated with a 215 micron thick kapton layer between them.

- Ferromagnetic layers (permeability between 11 and 18) & kapton (zero magnetic contribution) yielded magnetic permeability close to 3.5 desired for the Ratio $R_2/R_1 = 1.34$.

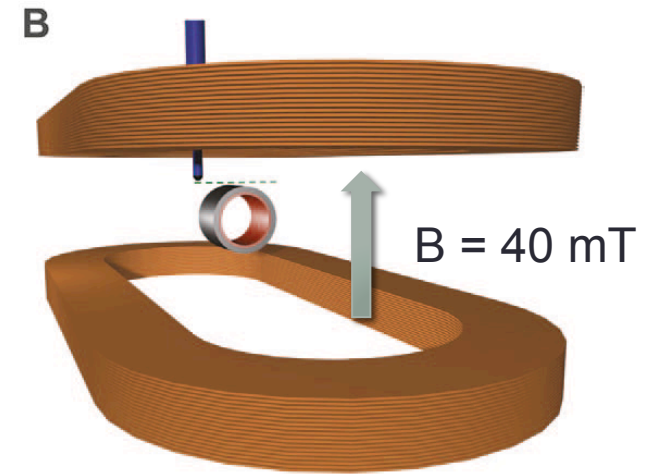
Realization

ferromagnetic:
 $\text{Fe}_{18}\text{Cr}_9\text{Ni}$
 $\mu_2 = 3.54$

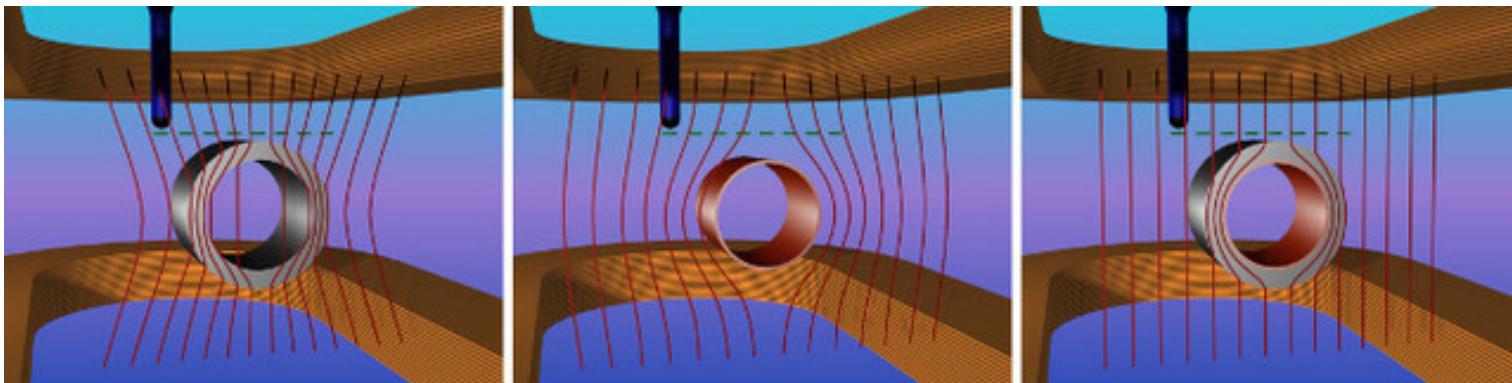
superconducting:
ReBCO
(cuprate HT-SC)



$L = 12 \text{ mm}$
 $\phi_{in} = 12.5 \text{ mm}$

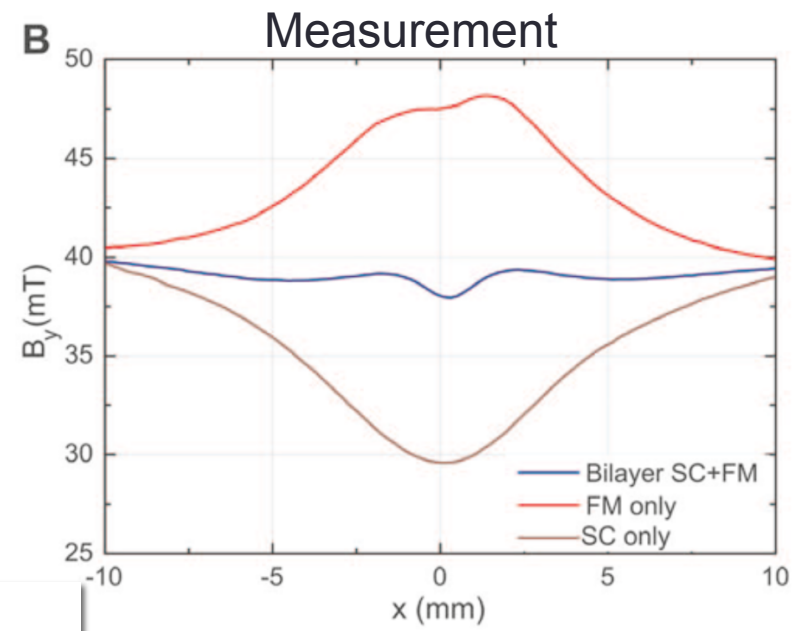
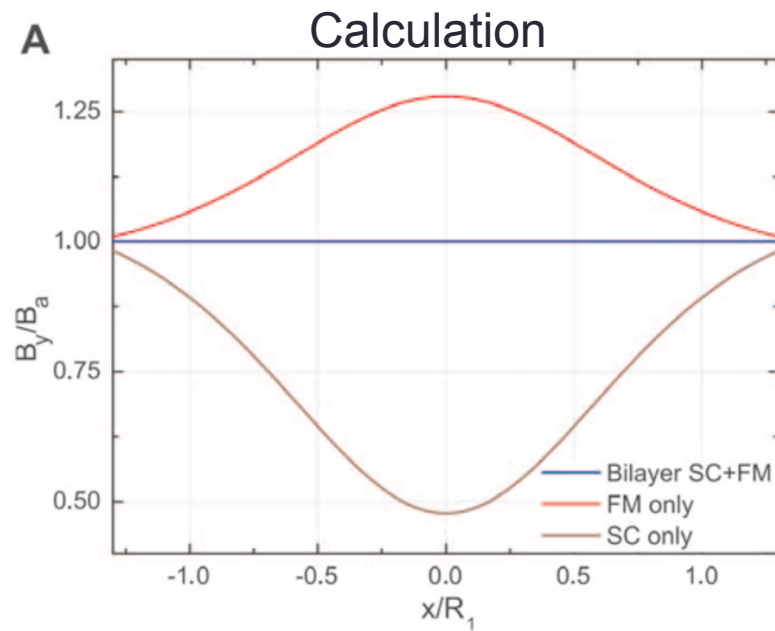


F. Gomory et al.
DOI: 10.1126/science.1218316



Testing the cloak

Fedor Gömöry et al.
DOI: 10.1126/science.1218316



Our strategy

Simulation

Simulate Gomory result using COMSOL program

- COMSOL Multiphysics is a finite element analysis, solver and simulation software package for various physics and engineering applications. Allows users to create models, specify materials and add all desired physics like magnetic fields, currents, mechanical stresses

Construct our desired geometry and simulate if the magnetic cloak works at larger dimensions needed for the EIC detector

- Study and understand the results and plan experimental tests

EXPERIMENTAL TEST:

Step 1: Proof of principle for high T_c SC sheet of ReBCO \rightarrow cool \rightarrow vicinity of high magnetic field. (suggested by Ramesh Gupta, BNL)

- Study the breakdown (seep-through) field values (expected to be ~ 40 -70 of mT)

Step 2: Build a prototype insert in known magnetic field, measure fields (in, out)

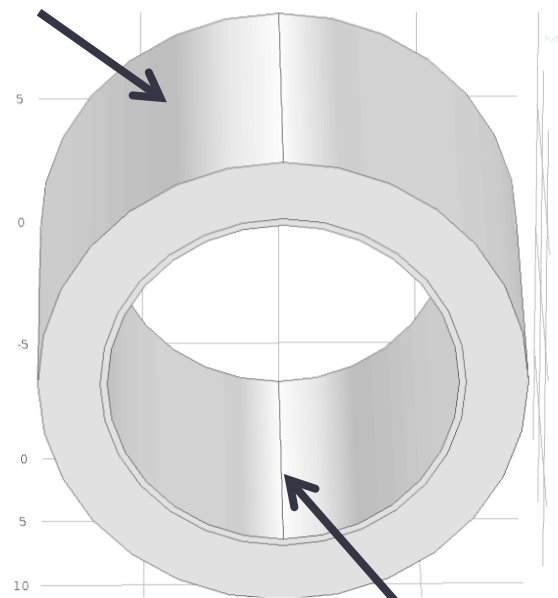
Step 3: In the Stony Brook tandem demonstrate the lack of defection on the beam when operated in the desired mode.

First tests with high T_c superconductors, then move on to low T_c SC's.

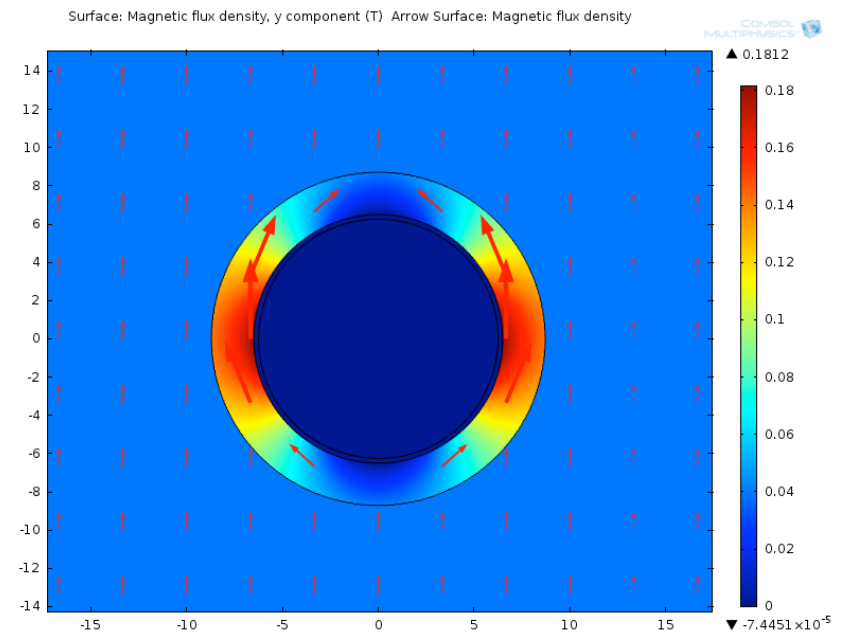
STEP N: Engineering design for RHIC

Our simulation of their device using COMSOL

$$\mu_{\text{FM}} = 3.54$$

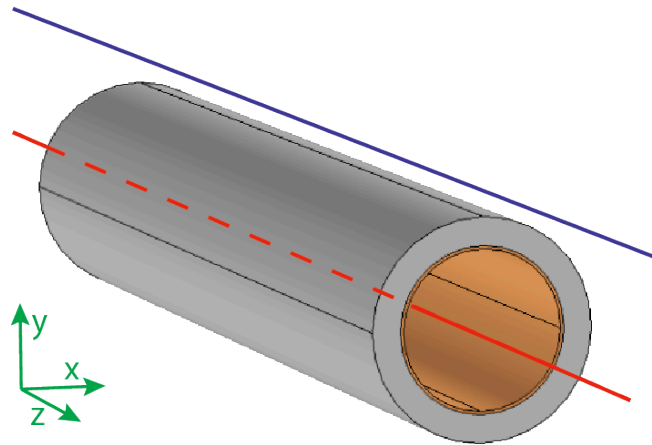


$$\mu_{\text{SC}} = 10^{-25}$$



Seems to work

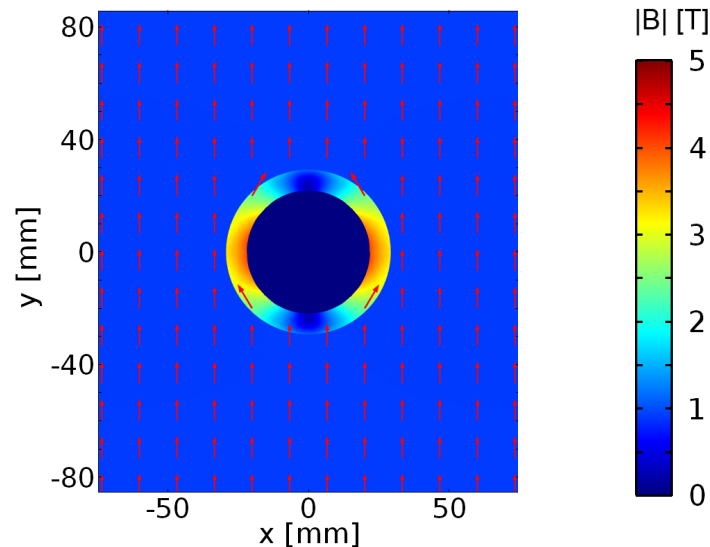
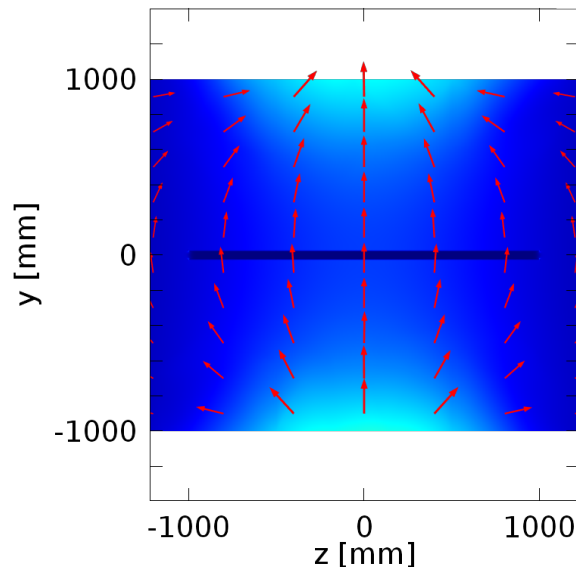
Put in a geometry for EIC cloak



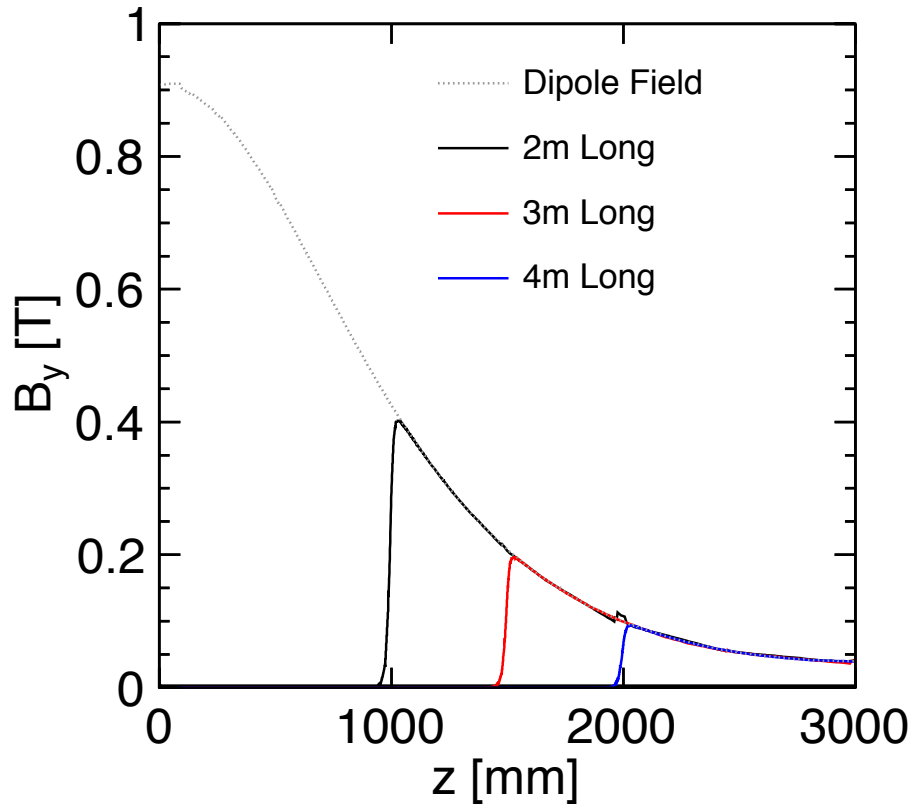
2m, 3m, 4m long cloaks

Dipole field provided in a region
 $1\text{m (z)} \times 2\text{m(x)} \times 2\text{m(y)}$

Studied the dependence of
shielding on radii and the shape
of the cloak



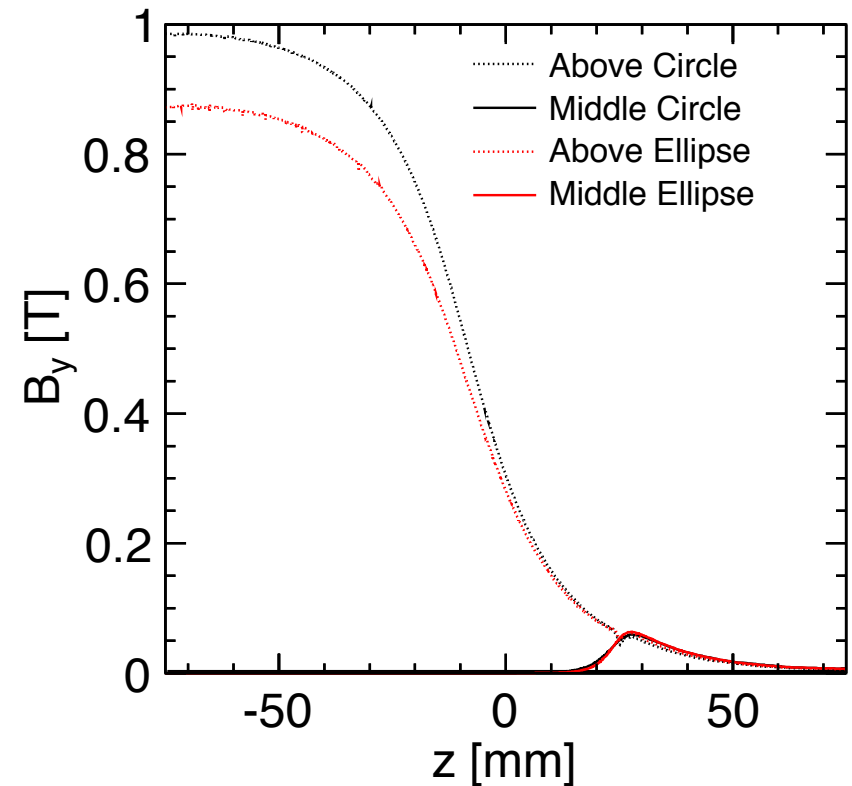
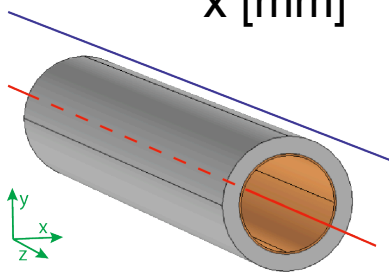
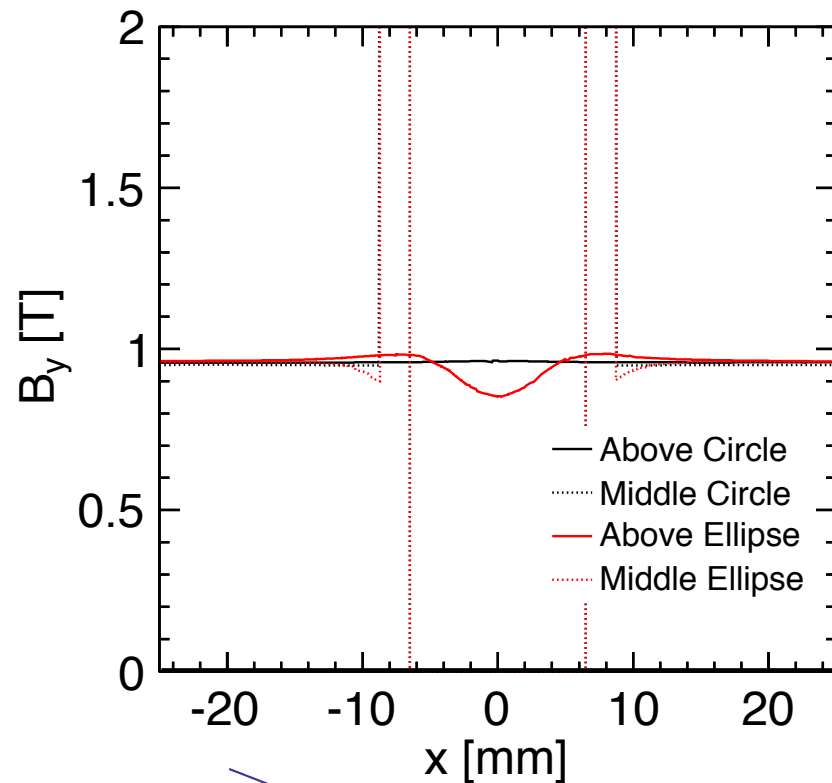
Cloak studies



- Inside the cloak the field drops to zero, in all cases
- Outside field is undisturbed
- Length of the cloak w.r.t. dipole field (left figure):
 - Thin line is the dipole field without the cloak
 - No field inside the cloak
 - Outside the cloak the field is unchanged from when there was no cloak
 - Kinks at the edge of the cloak → proportional to local field magnitude

A long cloak will create the desired tunnel for accelerator beams!

Non-circular cloak: elliptical $e=0.6$



Ellipse with eccentricity 0.6, other shapes will be checked with input from accelerator physicists

Qualitatively the same effects

Next: experiment and prototype construction

Simulate Gomory result completely using COMSOL program

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EXPERIMENTAL TEST: → THIS REQUEST

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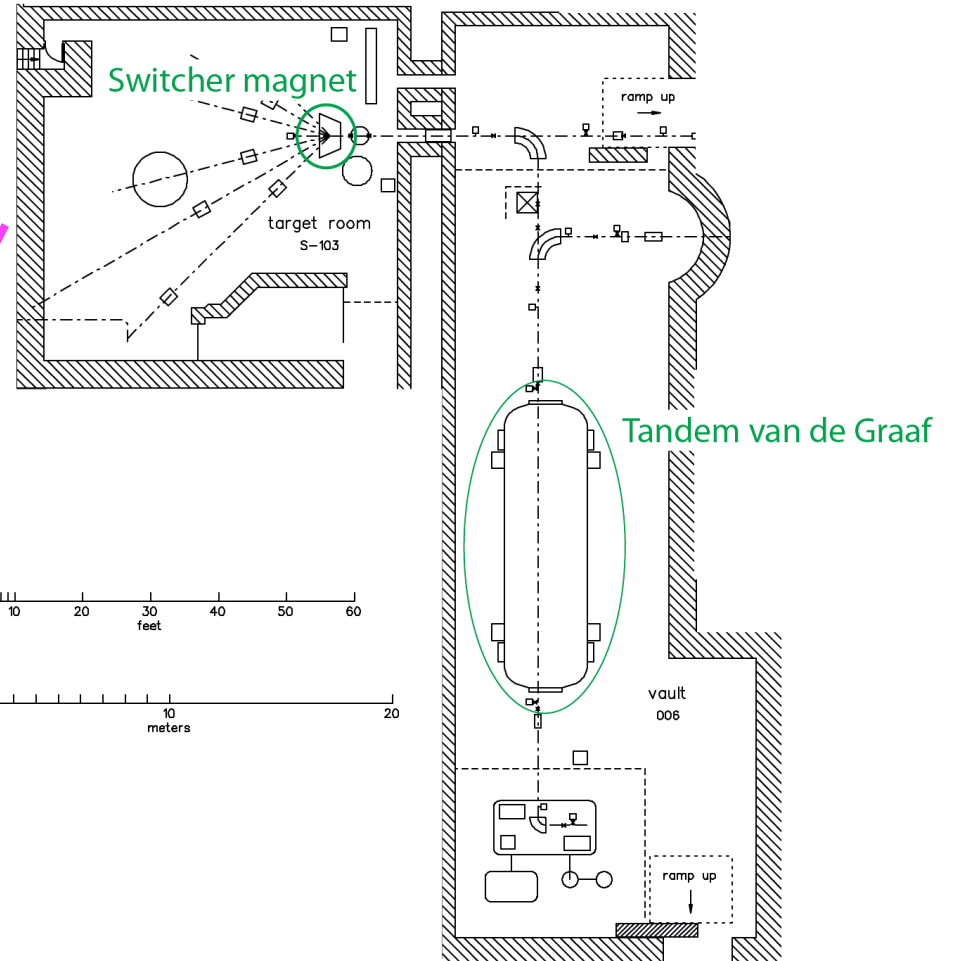
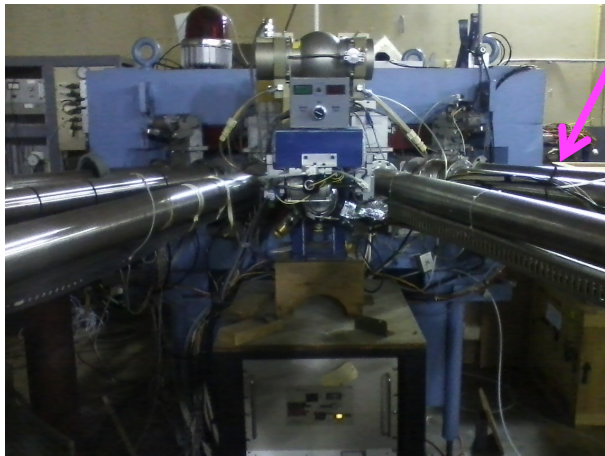
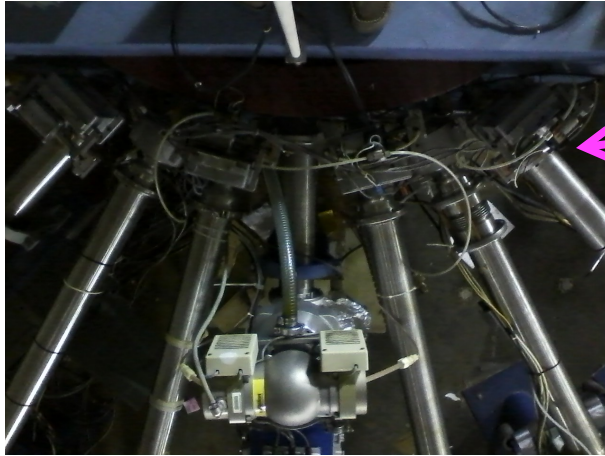
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STEP N: Engineering design for EIC(eRHIC/MEIC)/RHIC

Tandem at SBU

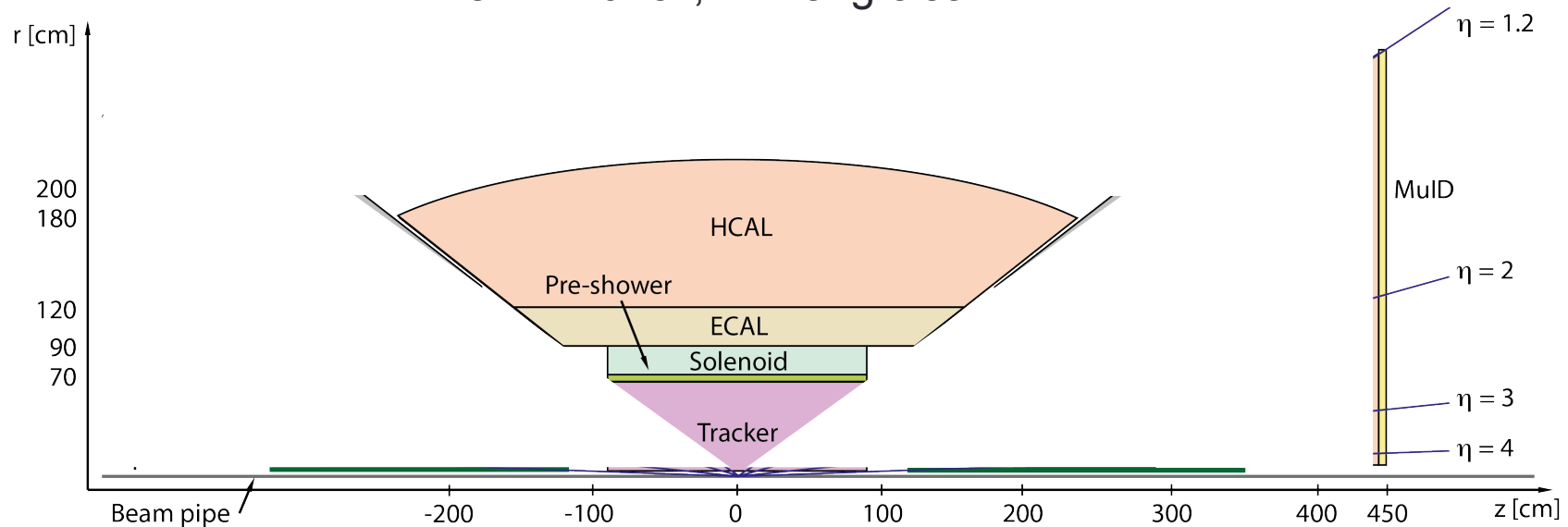


High vs. Low T_c

- **Will test first on the high T_c superconductors (HTSC):**
 - Cheap, locally available (Magnet Div) and also American Superconductors has a strong relation with BNL Mag Div
 - Easier to handle cooling: conduction/contact cooling, 77K
 - Nitrogen cheap
 - Lower critical breakdown field (40-80 mT), effect of cooling below 77K to be explored and understood (suggested by R. Gupta)
- **We will also test with low T_c superconductors (LTSC):**
 - 2m x 14 cm x 200 micron sheet for \$4k (Japanese manufacturer, works with g-2 collaboration), RIKEN Contact
 - More difficult to handle due to helium cooling temperatures, 4k
 - Helium expensive
 - Critical breakdown fields ~ 400 mT (safety margin if HTSC fails)

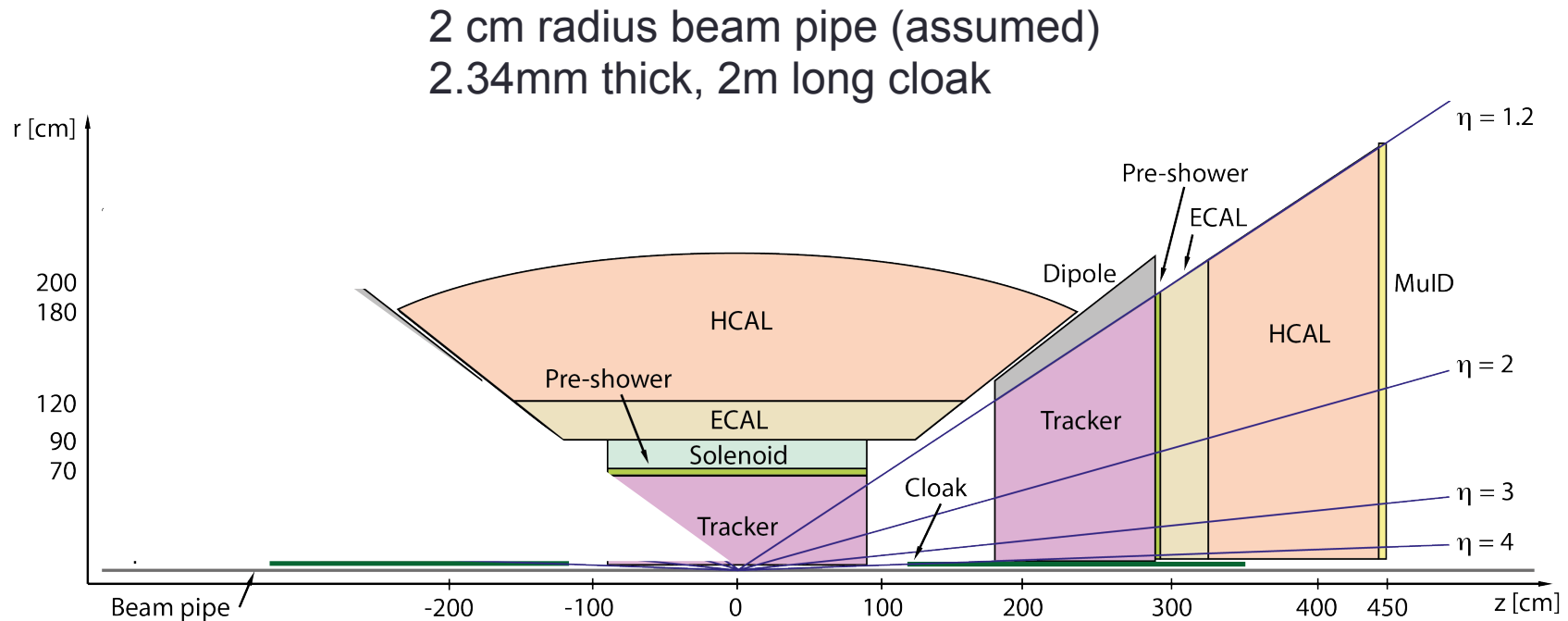
Schematic: sPHENIX-ePHENIX & the cloak

2 cm radius beam pipe (assumed)
2.34mm thick, 2m long cloak



sPHENIX

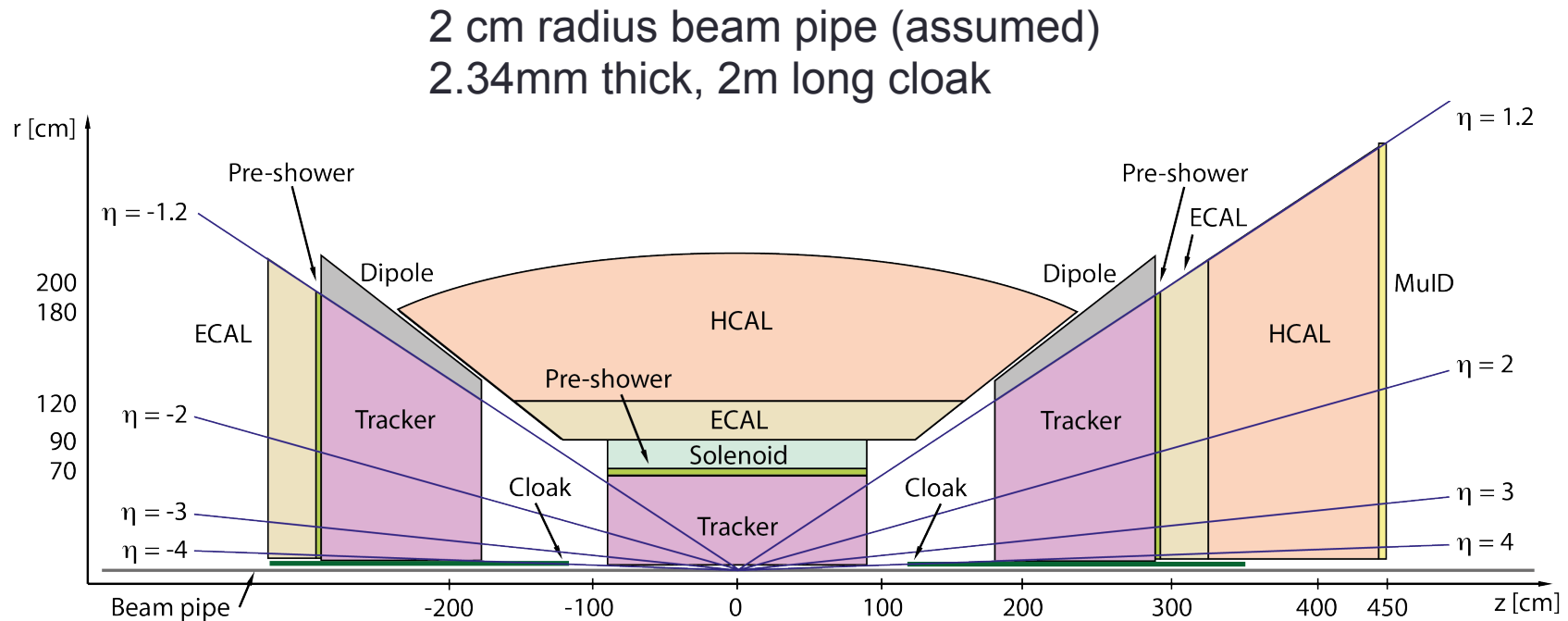
Schematic: sPHENIX-ePHENIX & the cloak



sPHENIX → ePHENIX-hadron-side

Engineering solutions will require close collaboration and involvement of the BNL magnet division and the CAD, and more funds. Outside the scope of current R&D.

Schematic: sPHENIX-ePHENIX & the cloak



sPHENIX → ePHENIX

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Preliminary budget:

Item	Cost estimate [\$]
Superconducting layers (high- and low- temperature superconductor)	10,000
Superconductor cooling (liquid nitrogen and helium)	10,000
Ferromagnetic layer	5,000
Test set-up, including machine shop (cloak support, hall probes, beam position monitor, temperature probes)	15,000
Solenoid magnet commissioning and operation	10,000
Student salary (2 UG summer salaries)	11,000
RIKEN contribution	-15,000
Total	46,000
Overhead (57%)	26,220
Total Budget Request	72,220

TBC

Summary:

- Magnetic cloak is an elegant device by itself, already being used in small sizes in medical fields.
 - If it can be scaled up → possible use in EIC, other detectors much before, and whether, the EIC is realized, and other accelerator applications: enormous potential
- The high T_c SC technology has developed over the past decade: now robust. Discussions with experts do **not** indicate conceptual show-stoppers for the present purpose.
- Exploratory **simulations done**: ***We now seek to test the concept by building a high T_c SC prototype.*** Upon success: this will be followed up with engineering designs for cooling in real beams and interaction regions.
- Appreciation for its use in the upgrade of PHENIX detector (in to an eRHIC detector: ePHENIX) has already attracted outside interest (RIKEN in particular, but also RBRC). **Anyone excited about this concept is welcome to join!**

Backups

Item	Phase 1	Phase 2	Total
Superconducting Layer: HTSC & LTSC	2000	8000	10000
Cooling: liquid nitrogen & helium	2000	8000	10000
Ferromagnetic layer	5000		5000
Test setup: Machine shop (cloak support, hall probes, temperature probes)	15000		15000
Solenoid magnet commissioning	10000		10000
Student summer salaries 2 x \$5.5k		11000	11000
Total	34000	27000	61000
RIKEN (TBC)		-15000	-15000
Total	34000	12000	46000
SBU 57% Overhead	19380	6840	26220
Total Request	53380	18840	72220

